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Study on sapphire removal for thin-film LEDs fabrication using CMP and dry etching

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ABSTRACT

Mechanical grinding, chemical mechanical polishing (CMP) and dry etching process are integrated to remove sapphire substrate for fabricating thin-film light-emitting diodes. The thinning of sapphire substrate is done by fast mechanical grinding followed by CMP. The CMP can remove or reduce most of the scratches produced by mechanical grinding, recovering both the mechanical strength and wafer warpage to their original status and resulting in a smoother surface. The surface morphology and surface roughness on grinded and polished sapphire substrate are measured by using atomic force microscopy (AFM). The etch rates of sapphire by BCl_3-based dry etching are reported. Pattern transfer to the physical and chemical stability of sapphire is made possible by inductively coupled plasma (ICP) etch system that generates high density plasma. The patterning of several microns period in sapphire wafer by using a combination of BCl_3/Ar plasma chemistry and SiO_2 mask is presented. The anisotropic etch profile formed on sapphire wafer is obtained from scanning electron microscopy (SEM) images.

1. Introduction

Recently, the Group-III nitride based semiconductors have emerged as the leading materials for realization of high performance light emitters from ultraviolet (UV) to the blue and green spectral regions [1–4]. Generally, GaN-based light-emitting diodes (LEDs) are grown on the sapphire (Al_2O_3) substrate. Although the deposition of low temperature nucleation layer such as GaN and AlN on sapphire substrate can improve the crystal quality of the subsequent GaN epitaxial layers, the threading dislocation density between 10^8 and 10^{10} cm^{-2} will still remain due to the large mismatch in lattice constants and thermal expansion coefficients between the nitride epi-layer and sapphire substrate. Thus, we need to reduce the threading dislocation density in order to improve the performance of GaN-based LED. GaN-based LED grown on the patterned sapphire substrate can improve the internal quantum efficiency by the reduction of threading dislocation density [5]. It is well known that sapphire is chemically inert and insoluble in most substances. Therefore, it is extremely difficult to etch or pattern the sapphire substrate with wet chemical etching at room temperature. Compared with wet etching, dry etching can provide an anisotropic profile and a fast etching rate. Much of the previous work has investigated several etch techniques such as chemical wet etching after ion implantation [6], reactive ion etching [7], laser-induced etching [8,9], and inductively coupled plasma etching (ICP) [10,11]. BCl_3-based gas chemistry is widely used to etch sapphire because B scavenges oxygen, and it forms $BOCl_x$ volatile etch products [12]. BCl_3/Cl_2 and BCl_3/Cl_2/Ar gas combinations have been reported to have high etching rates for sapphire etching but poor etch selectivities over a photoresist. Therefore, to use hardmasks such as SiO_2 instead of photoresist as etch mask and to achieve more anisotropic etch profiles were required.

Thin-film LEDs with vertical structure electrodes are widely employed for fabricating high power LED [13]. To fabricate thin-film LEDs, sapphire substrate must be removed due to its non-electrical conductivity and low thermal conductivity. Generally, sapphire substrate is removed by laser lift-off (LLO) process [14,15]. However, the LLO method has some drawbacks. During the LLO process, the temperature should be above 900 °C in the GaN/sapphire interface due to the absorbed photon energy, leading to the destruction of the GaN. Another drawback of this approach lies in that the bonding layer can be affected, because the bonding layer is only several microns away from GaN/sapphire interface [16].

In this paper, we combine mechanical grinding with chemical mechanical polishing (CMP) and dry etching to remove sapphire

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substrate. The BCl_3/Ar gas combinations are used to etch and pattern (0 0 0 1) oriented sapphire substrate. The etch characteristics of sapphire wafers are investigated.

2. Experiments

For etch rate experiments, we used (0 0 0 1) oriented sapphire as etch samples. A layer of SiO_2 mask was deposited by plasma-enhanced chemical vapor deposition (PECVD) on the top of sapphire. The etch depth of sapphire was measured by profilometry. The etch profile of sapphire was obtained from scanning electron microscopy (SEM) images. All etching was carried out in an ICP etcher (Oxford Plasma Lab System 100). The plasma was generated by a radio frequency (13.56 MHz) glow discharge.

To conduct the experiment for separating sapphire substrate from GaN epitaxial layer, LED wafer was used as the experimental sample. The LED structure consists of a 375-μm-thick sapphire substrate, a 2-μm-thick unintentionally doped GaN, a 2-μm-thick n-GaN layer, an active region with ten periods of InGaN/GaN muitiple quantum well, and a 0.2-μm-thick p-GaN. GaN epitaxial layer was grown on the sapphire substrate by metal organic chemical vapor deposition (MOCVD). To detach sapphire substrate from GaN epitaxial layers, the LED wafer was first flip bonded to silicon substrate by Au–Sn eutectic bonds. Afterwards sapphire substrate was thinned from 375 μm to around 100 μm by mechanical grinding including coarse and fine grinding, then sapphire substrate was thinned from 100 μm to about 8 μm by CMP, finally dry etching was used to remove the remaining sapphire substrate. The surface morphology and surface roughness were measured on sapphire substrate using atomic force microscopy (AFM).

3. Results and discussion

The etch rate of sapphire as a function of BCl_3 concentrations in BCl_3/Ar gas chemistry was shown in Fig. 1. During the etching process, the ICP power and RF power were kept at 1500 W and 150 W, respectively. The total gas flow was 60 sccm. The DC bias voltage decreased from −325 V for 90% BCl_3/10%Ar to −259 V for 10% BCl_3/90%Ar.

As shown in Fig. 1, the increase of BCl_3 in BCl_3/Ar generally increased the sapphire etch rate. The increase of BCl_3 in BCl_3/Ar rapidly increased sapphire etch rates until 30% BCl_3 was reached due in part to higher concentration of reactive radicals such as BCl, Cl which increased the chemical etching of sapphire. However, sapphire etching rates did not increase much faster above 30% BCl_3 in BCl_3/Ar according to the slope of line segment shown in Fig. 1. During the etching process, when BCl_3 percent increased from 10% to 30%, 30% to 50%, 50% to 70%, and 70% to 90%, the increment of DC bias voltage was 25 V, 12 V, 15 V, and 14 V, respectively. This indicated that the increment of DC bias voltage in high BCl_3 percent region was much smaller than that in low BCl_3 percent region. Therefore, the increment of sputtering yield in high BCl_3 percent region could be much smaller than that in low BCl_3 percent region due to the smaller increment of DC bias voltage in high BCl_3 percent region. Meanwhile, the increment of chemical etching yield in high BCl_3 percent region could be much smaller than that in low BCl_3 percent region due to the smaller increment of reactive radicals density in high BCl_3 percent region [17]. Besides, the Langmuir probe diagnostics of the BCl_3/Ar gas plasma indicated that the ion density in BCl_3/Ar gas plasma increased with increasing Ar fraction [17–19]. In other words, the ion density in BCl_3/Ar gas plasma decreased with increasing BCl_3 fraction, which would cause the decrease of ion-assisted etching rate in high BCl_3 percent region. Accordingly, the reason that sapphire etching rates did not increase much faster above 30% BCl_3 in BCl_3/Ar was related to the smaller increment of DC bias voltage and reactive radicals density in high BCl_3 percent region, and to the decrease of ion density in high BCl_3 percent region.

Fig. 2 showed that the sapphire etch rates as a function of BCl_3 gas flow in pure BCl_3 gas chemistry while the ICP power, RF power, operating pressure were 600 W, 150 W, and 5 mTorr, respectively. The etch rates of sapphire increased with the increasing BCl_3 gas flow up to 50 sccm and further increase of BCl_3 decreased the etch rates slightly at specific ICP/RF power. It is noted that the DC bias voltage showed only small change, from −430 V at 10 sccm to −432 V at 70 sccm, and the small change in the DC bias voltage was not expected to be a critical factor in the change in etch rate. The exact reasons for the slight decrease in sapphire etching rate when the pure BCl_3 gas flow up to 70 sccm were not clear at this moment. It might be related to either saturation of reactive species at the sapphire surface or sputter desorption of reactive species from the sapphire surface before the occurrence of chemical reactions [20].

The effect of operating pressure on the sapphire etch rates was investigated while maintaining the BCl_3/Ar mixture ratio at 90%/10%, ICP power and RF power at 2000 W and 100 W, respectively. As a function of operating pressure, plasma condition including the mean free path can change leading to changes in both ion energy and plasma density. Sapphire etch rates were plotted as a function of operating pressure in Fig. 3. As shown in Fig. 3, the increase of operating pressure from 3.6 mTorr to 9 mTorr decreased the sapphire etch rates from 1831 Å/min to 1549 Å/min. In general, the

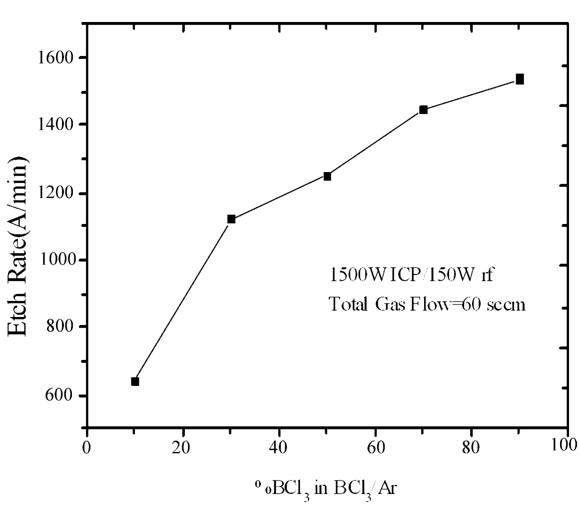

Fig. 1. Etch rate of sapphire as a function of %BCl_3 in BCl_3/Ar gas chemistry.

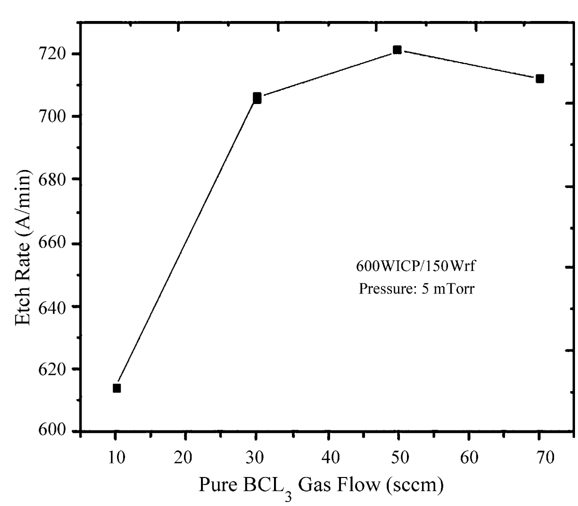

Fig. 2. Etch rate of sapphire as a function of BCl_3 gas flow in pure BCl_3 gas chemistry.